CCL 3/19/97 1.322 Consolidation Part V
3/14/99
3/01

V TWO & THREE DIMENSIONAL LOADINGS

Sheets A, B1, B2 Method to estimate ρ_e & ρ_i
Sheet C Recomp. vs SHANSEP CK_0U E_u/σ'_{vc}
Sheets D1, D2 Skempton-Bjerrum method
Sheet E Effect of lateral drainage on $\bar{U}$
Sheet F Elastic method of estimating ρ_i & ρ_{cf}

1 INTRODUCTION

1.1 Stress Paths (Fig.1, p1a) NOTES: Review of 1.361 Part V 5

1) 1-D Loading $TSP = TSP - u_s = 0a\bar{b}$ $ESP = 0\bar{b}$

- ε_{vert} vs t for ℄ element with $Z = z/H_d \approx 1$

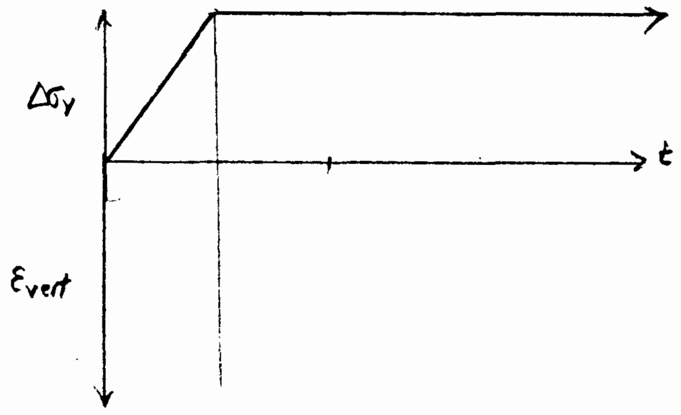
2) 2-D Loading a) Undrained loading $TSP = 012$ $ESP = 0\bar{1}$

b) Consolidation $TSP = 24$ $ESP = \bar{1}\bar{4}$

Undrained Loading ↓ ρ_i
- What happens at Pt 1?
- What is Contained Plastic Flow (CPF)?
- What differs if get strain-softening?
- Can Δu be $> \Delta\sigma_v$?
- ε_{vert} vs t

Consolidation ↓ ρ_{cf}
- Why Pt $\bar{4} = 4 \neq 3$?
- ε_{vert} vs t

1.2 Strain vs. Time for ℄ Element



- Effect of undrained creep
- Effect of lateral drainage

1.3 Total Settlement (w/o secondary compression)

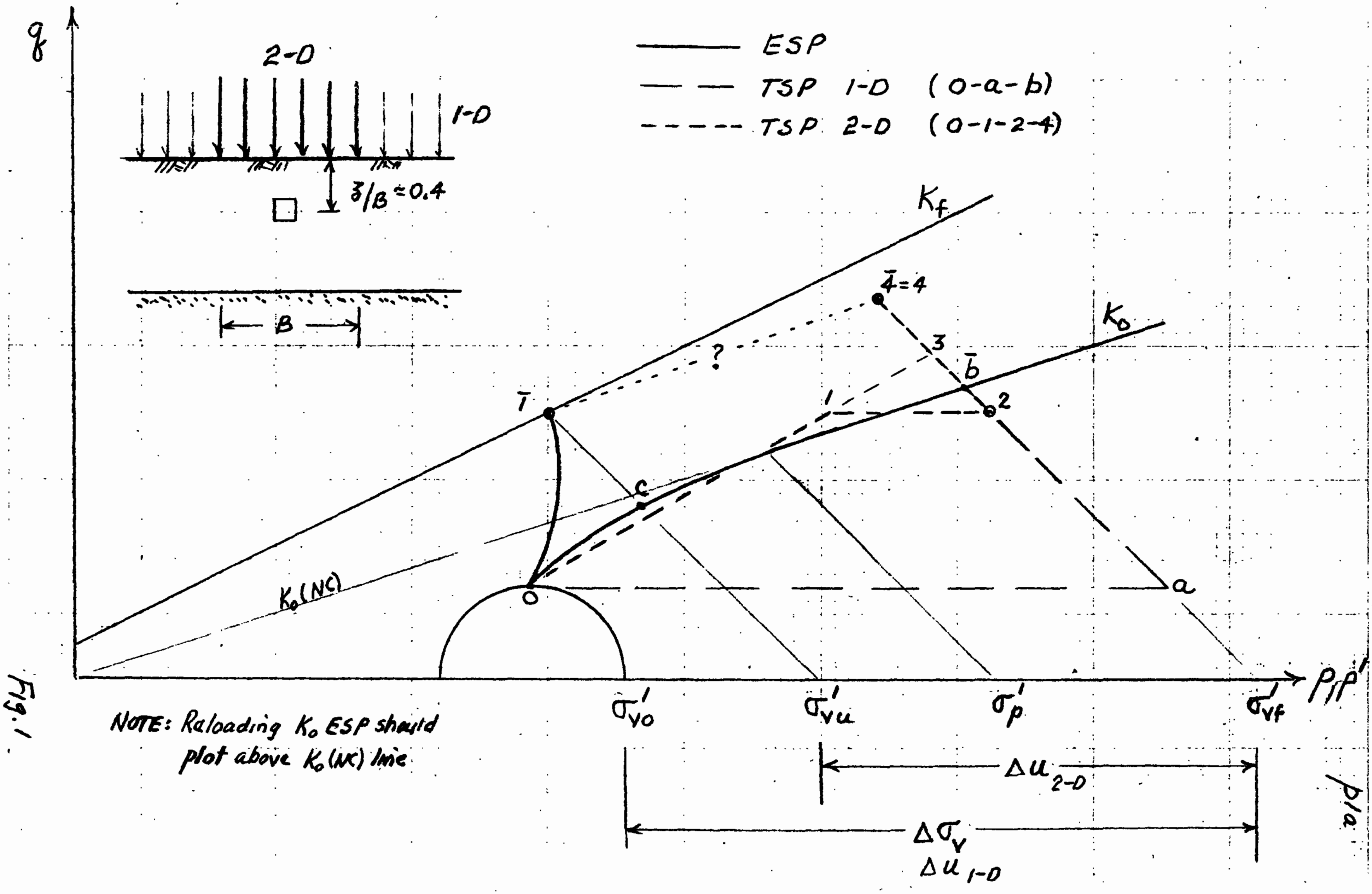
1) 1-D : $\rho_T = \rho_{cf} = \rho_{oed}$

2) 2,3-D : $\rho_T = \rho_i + \rho_{cf}$; $\rho_{cf} \neq \rho_{oed}$

3/97 3/99
CCL 3/82
1.322

STRESS PATHS FOR 1-D & 2-D LOADINGS

Slightly O.C. Sat. Clay , F.S. ≈ 1.5



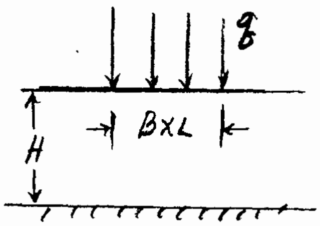
NOTE: Reloading K_o ESP should plot above K_o(NC) line

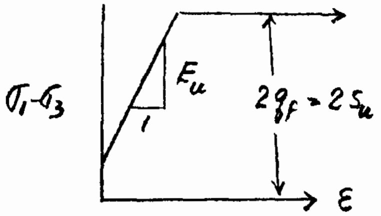
Fig. 1

2. INITIAL SETTLEMENT (Undrained Loading)

NOTE: Based on D'Appolonia et al. (1971) & Foott & Ladd (1981)
ASCE, JSMFD, 97(10), 1359-1377 ASCE, JGED, 107(8), 1079-1094

2.1 Geometry and Stress-Strain Model





- Finite element analyses with bi-linear model (actually, $E_t > 0$ after yielding)

2.2 Load vs. Settlement

1) Overview

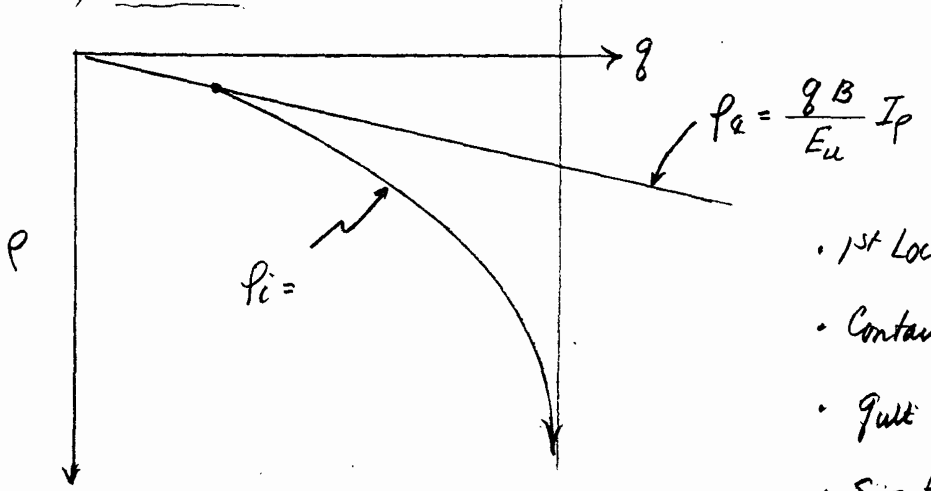
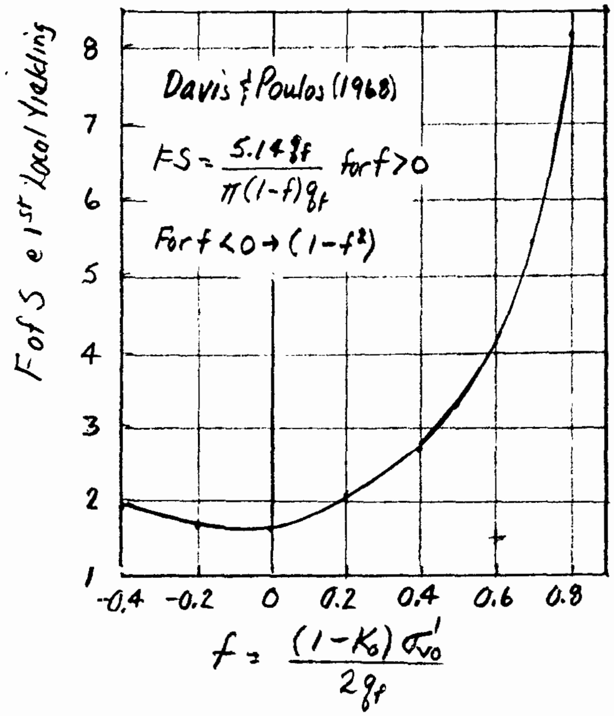


Fig 6, Sheet A
$I_\rho = f(?)$

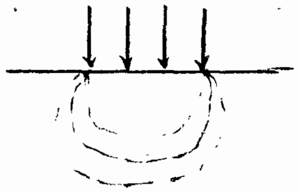
- 1st Local Yielding (LY)
- Contained Plastic Flow
- q_{ult}
- $S_R = \rho_e / \rho_i$

2) Factor of Safety @ 1st LY (Strip Load on isotropic, homogeneous clay)



- Physical meaning of f =

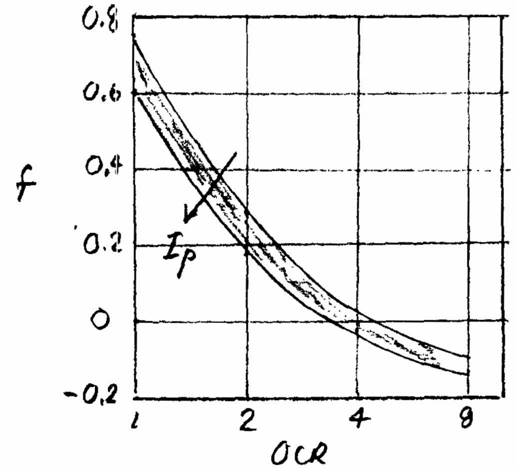
- Location of 1st LY



- How obtain f ?

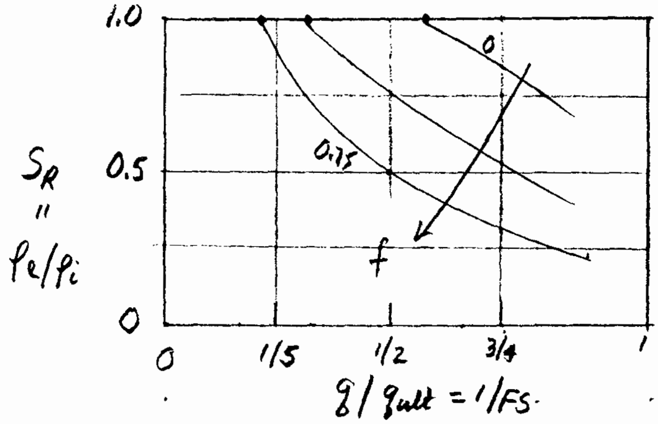
- For OCR = 1, FS ≈

3) Estimation of f (Sheet B1)



- NC f = → FS_{LY} =
- f = 0 @ OCR ≈ → $FS_{LY} = 1.65$

4) Estimation of $S_R = f[H/B, 1/FS \; \& \; f]$ (Sheet B2)



- Significance of when S_R 1st < 1.00
- At same FS & f, increasing H/B → more/less affect of CPF?

For H/B = 1

FS	f	p_i/p_e
2	0.25	1.0
	0.75	2.0
	0	1.25
1.25	0.25	1.6
	0.75	3.7

Conclusion low FS & especially low OCR
→ high p_i/p_e

2.3 Definition of s_u (say for ship loading)

1) For f > 0 s_u = ___ for shear in ___ since 1st LY @ ___

2) For f < 0 s_u = ___ " " " ___ " " " " ___

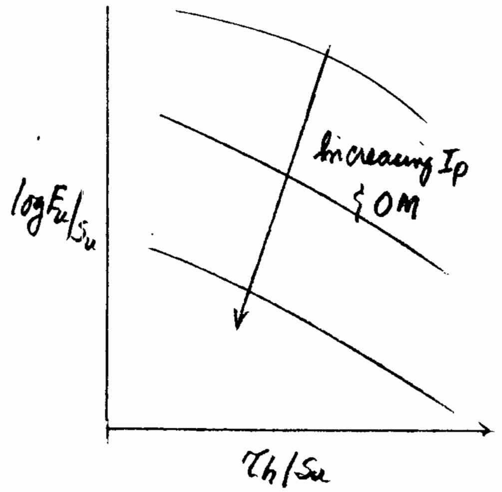
3) For FS using BC eqn s_u = ___ for shear ___.

4) " " " circular arc s_u = ___ for shear ___

3/13/01

2.4 Estimation of E_u for ρ_e

1) Foott & Ladd ('81) Recommendation for Est. E_u/s_u (Sheet A, Fig 5)



- Test data from ________

- How select value of τ_h/s_u?

; For NC Soil @ FS ≈ 1.5

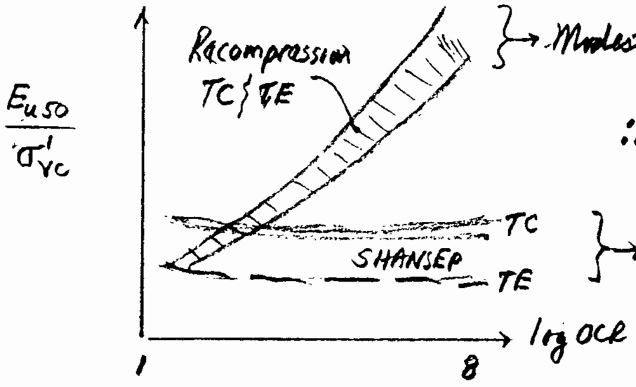
Soil	E_u/s_u	
① Lean sensitive	800	Why too low?
④ Me. Org	250	— Signif. ρ_i, δ_h during constr.*
⑤ EABPL	90	} Caused large problems during - after construction
⑥ TR Peat	40	

* See TL, CCL ('91), p 599-602

- Incr. OCR → E_u/s_u ↑ or ↓ ?

- Application to structured clays → est. ρ_i much too ____

2) Recompression vs SHANSEP CK_0UC/E data on natural BBC (Sheet C)

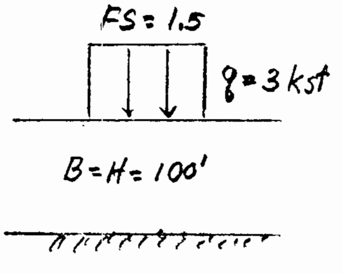


} → Modest increase in E_u/s_u with increasing OCR

∴ Should use Recompr. CK_0U tests for reliable E_u/s_u with structured OC clays

} → Decreasing E_u/s_u with incr. OCR à la Sheet A, Fig. 5(b)

3) Examples of ρ_i vs Soil Type



$$\rho_e\,(in.) = \frac{2100}{E_u/s_u}$$

Soil Type	E_u/s_u	ρ_e (in)	ρ_i for $S_R = 0.5$
Cemented Canadian	1500 (±500)	1.4	2.8"
Typical CL→CH	300 (±200)	7	14" = 1.2' = 35 cm
Peat	50 (±20)	42	7' = 2.1 m

2.5 Conditions Leading to Large ρ_i

1. Highly plastic-organic → low E_u/s_u → large ρ_e
2. Low FS and OCR } → increasing ρ_i/ρ_e, plus increase ρ_e
3. Slow consolidation → increasing ρ_i with time due to "undrained" creep (plus slow $+\Delta s_u$ → little $+\Delta E_u$)

Probably ok to estimate E_u/s_u from SHANSEP CK_oUDSS

3. FINAL CONSOLIDATION SETTLEMENT (ρ_{cf})

3.1 Calculation Methods (Review 1.361 Part V-5 & HP No. 12)

1) Conventional Practice $\rho_{cf} = \rho_{oed} = \Sigma H_i (\varepsilon_{cf} = RR \log \sigma'_p/\sigma'_{vo} + CR \log \sigma'_{vf}/\sigma'_p)$

- HOW COMPUTE $\Delta\sigma_v$?

ESP =

Actual ESP =

2) Skempton-Bjerrum (Sheets D1 & 2)

Assumed ESP =

- How compute $\Delta\sigma_v$?

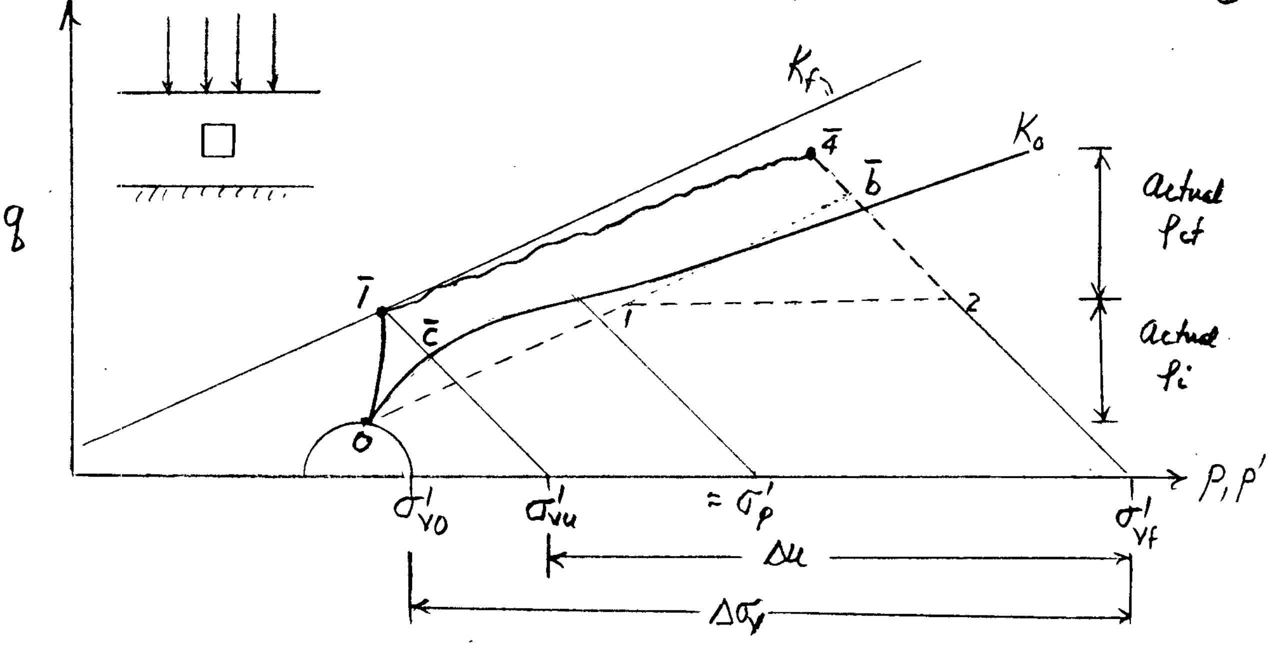
$\rho_{cf} = \rho_{oed} \times$ ________

- When UNSAFE (Sheet D2)

How estimate A?

3) CCL modification to S-B = Replace σ'_{vo} by σ'_{vu}

- How estimate $\Delta u = \Delta\sigma_h + A(\Delta\sigma_v - \Delta\sigma_h)$?



3.2 Rate of Consolidation Settlement (Without Vertical Drains)

1) See Sheet E for examples of effect of lateral drainage on increased $\bar{U}$ vs T_v based on elastic soil model

2) For important jobs with variable stress history, etc., need finite element analyses with "generalized" soil model such as MCC or MIT-E3

3) Ladd, Whittle & LeGaspi (1994) "Stress-Deformation Behavior of an Embankment on Boston Blue Clay" ASCE Settlement '94 GSP No. 4 compares MCC & MIT-E3 predictions with measured u, ρ & δh.

4 RELATIVE IMPORTANCE OF ρ_i VS ρ_{ct} AND ρ_T VS ρ_{oed}

- Conventional practice: Compute z vs $\Delta\sigma_v$ and assume $\rho_T = \rho_{oed}$

4.1 "Stiff" Ground Condition ($\sigma'_{vf} < \sigma'_p$)

1) Since all recompression with low A, ρ_{ct} will be $< \rho_{oed}$ since $\Delta u < \Delta\sigma_v$

2) But $\rho_i \approx \rho_e$ often significant fraction of ρ_{ct}.
Several "old" case histories suggest $\rho_i/\rho_T \approx 0.5 \pm 0.25$

3) Hence $\rho_T \approx \rho_{oed}$ due to compensating errors

4) For important jobs, make separate estimates of ρ_i and $\rho_{ct} = \mu\rho_{oed}$, esp. when predicting rates of ρ_c

4.2 "Soft" Ground Condition ($\sigma'_{vf} > \sigma'_p$)

1) Have significant virgin compression → "large" ρ_{ct}

2) $\rho_T = \rho_i + (\rho_{ct} = \rho_{oed})$
↳ usually small compared to ρ_{ct}, But see Section 2.5

e.g. PPG chemical storage tanks → law suit with D&M

EABPL ΔEl. ≈ 15' → $\Sigma\rho \approx$ 35' from 1935 → 1960
↳ flood control levees on 120' of deltaic CH clay near Gulf of Mexico

NOTE: There are very few well documented case histories with definitive measurements of ρ_i & ρ_{ct}

43 Davis & Poulos (1968) Elastic Method (Sheet F)

1) Assumes that elastic theory can be used to relate undrained & drained deformations, ie,

$$E_u = 3G = \frac{3E'}{2(1+\nu')}$$

2) Method of calculating settlements $I_\rho = f(B/L, H/B \,\&\, \nu)$

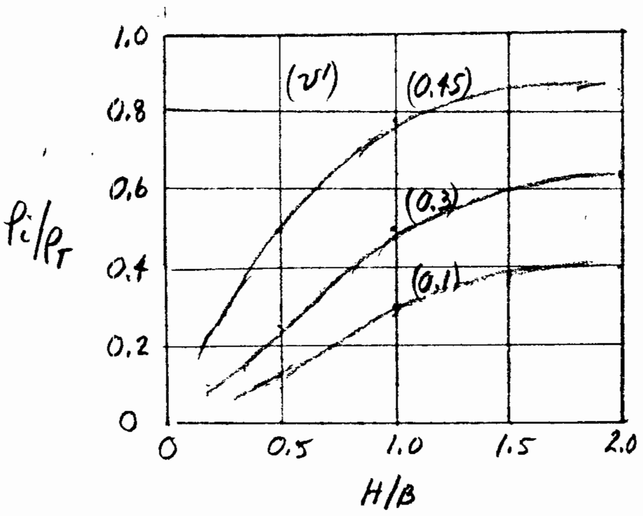
Initial $\rho_i = \frac{qB}{E_u} I_\rho$ with $\nu = 0.5$

Total $\rho_T = \frac{qB}{E'} I_\rho$ with $\nu = \nu'$

$\Big\}\ \rho_{ct} = \rho_T - \rho_i$

(Oed $\rho_{oed} = \frac{qB}{E'} I_\rho$ with $\nu = \nu' = 0 \rightarrow E' = \frac{1}{m_v}$)

3) Trends



- For circular load on elastic half space with $\nu' = 0.25$

  $\rho_i/\rho_T = 0.67$ ← very large

  $\rho_{ct}/\rho_T = 0.33$

  $\rho_{oed}/\rho_T = 0.89$

4) CCL opinion for low OCR clays: Method → ρ_i/ρ_{ct} much too high

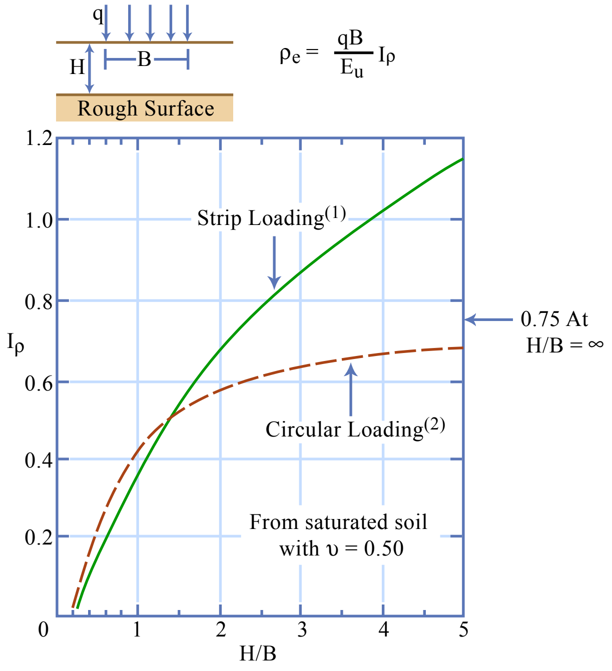
(BBC example for Tokyo '77)

- If reliable undrained G (e.g. E_u), then predicted ρ_{ct} much too small
- " " drained G (ie, from m_v & ν'), then predicted ρ_i much too large

5) Conclusion: Maybe ok for OC clays with all recompression, but very unreliable for low OCR clays with mostly virgin compression.

CCL 12/7/95

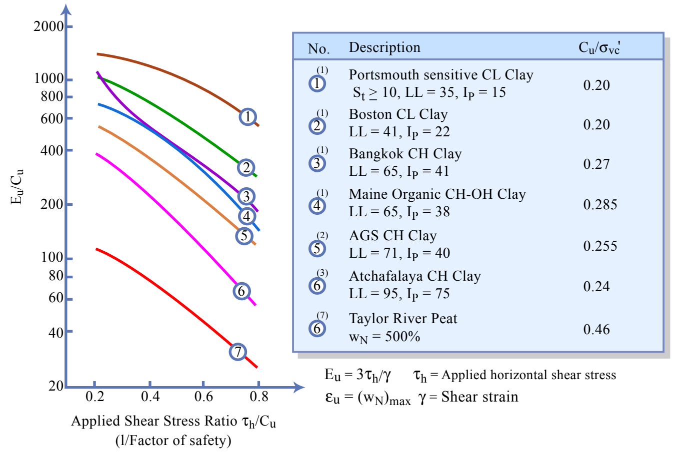
1.361-1.366 Part V-5



Undrained Elastic Settlement Computation for Uniform Loading on Elastic Layer

Figures by MIT OCW.

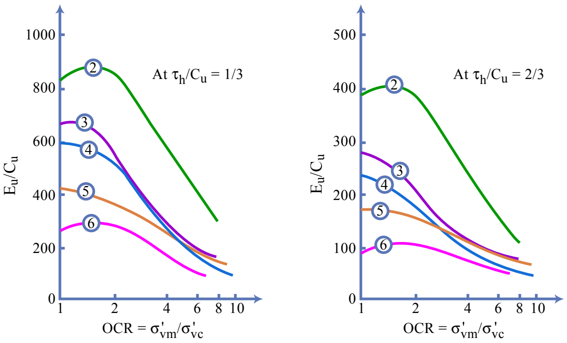
Adapted from: Initial Settlement (p1/2)
D'Appolonia et al. (1971)
Foott & Ladd (1981)



No.	Description	C_u/σ_{vc}'
①[1]	Portsmouth sensitive CL Clay $S_t \geq 10$, LL = 35, $I_P = 15$	0.20
②[1]	Boston CL Clay LL = 41, $I_P = 22$	0.20
③[1]	Bangkok CH Clay LL = 65, $I_P = 41$	0.27
④[1]	Maine Organic CH-OH Clay LL = 65, $I_P = 38$	0.285
⑤[2]	AGS CH Clay LL = 71, $I_P = 40$	0.255
⑥[3]	Atchafalaya CH Clay LL = 95, $I_P = 75$	0.24
⑥[7]	Taylor River Peat $w_N = 500\%$	0.46

$E_u = 3\tau_h/\gamma$ τ_h = Applied horizontal shear stress
$\varepsilon_u = (w_N)_{max}$ γ = Shear strain

(a) Normalized Secant Modulus vs. Stress Level for Normally Consolidated Soils



(b) Normalized Secant Modulus vs. Overconsolidation Ratio

Normalized Modulus Data from K_o-Consolidated Undrained Direct Simple Shear Tests

CCL 3/97

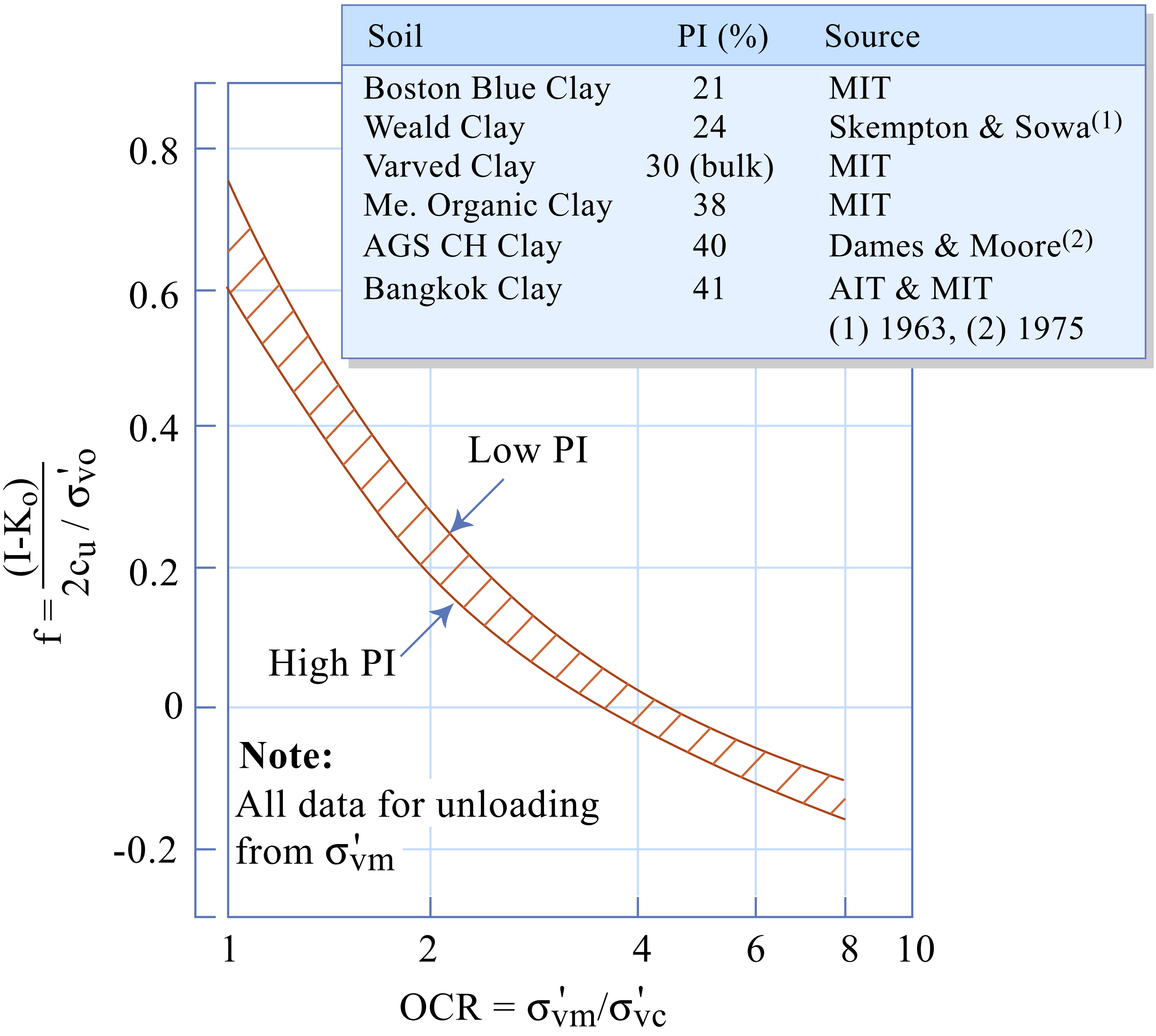
1.322 Consd. Part V

Ⓐ

1,322

CCL 3/88
3/99

Consolidation Part V



Soil	PI (%)	Source
Boston Blue Clay	21	MIT
Weald Clay	24	Skempton & Sowa(1)
Varved Clay	30 (bulk)	MIT
Me. Organic Clay	38	MIT
AGS CH Clay	40	Dames & Moore(2)
Bangkok Clay	41	AIT & MIT
		(1) 1963, (2) 1975

Note:

$c_u = 0.5\ (\sigma_1 - \sigma_3)_f$ from CK_oU triaxial or plane strain tests.
K_o from Brooker and Ireland (1965) for Me. Organic Clay.

Figure by MIT OCW.

Adapted from:

INITIAL SHEAR STRESS RATIO VS OCR

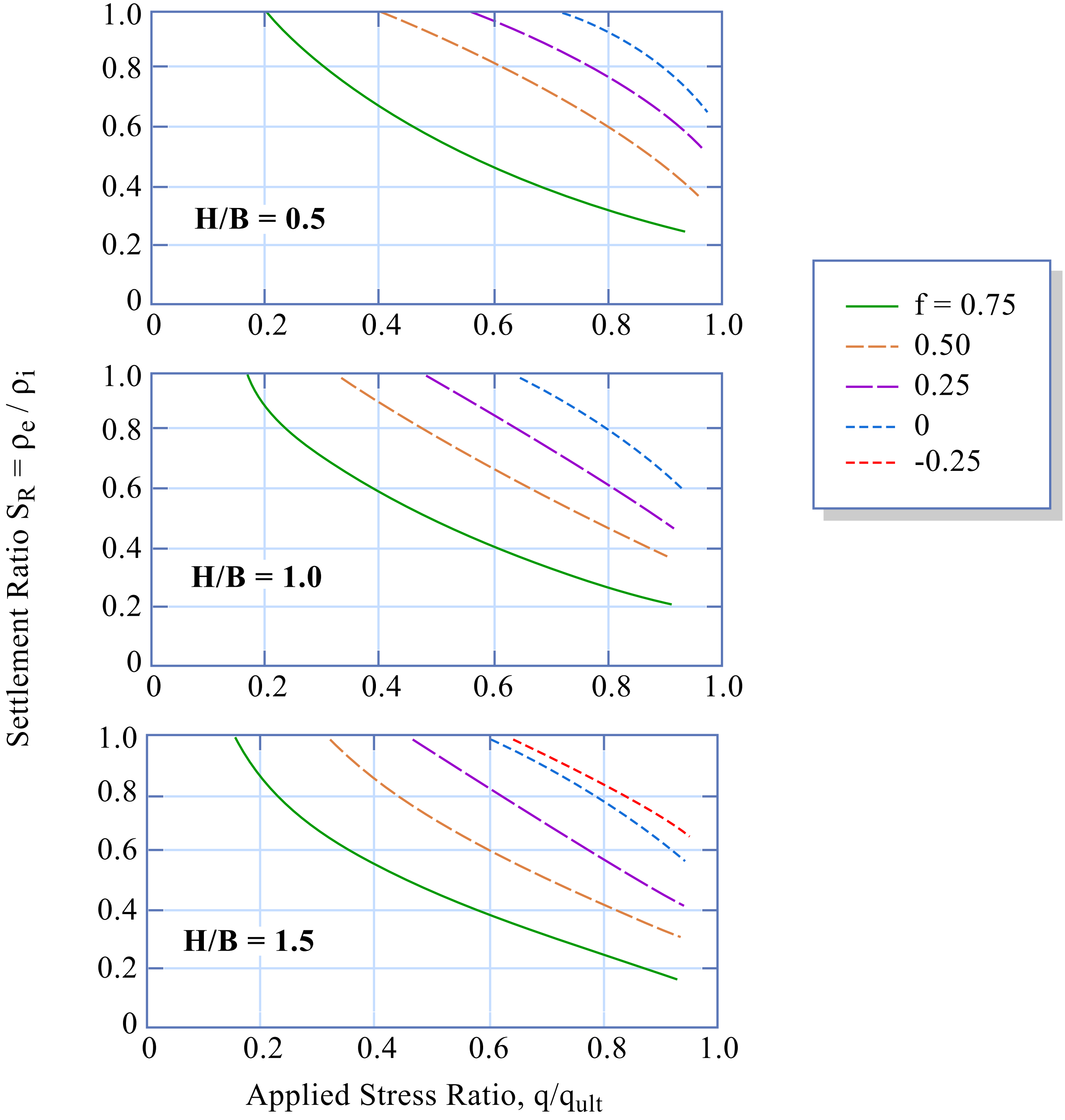
Ladd et al. (1977)

B1

1.322

CCL 3/99

Consolidation Part V



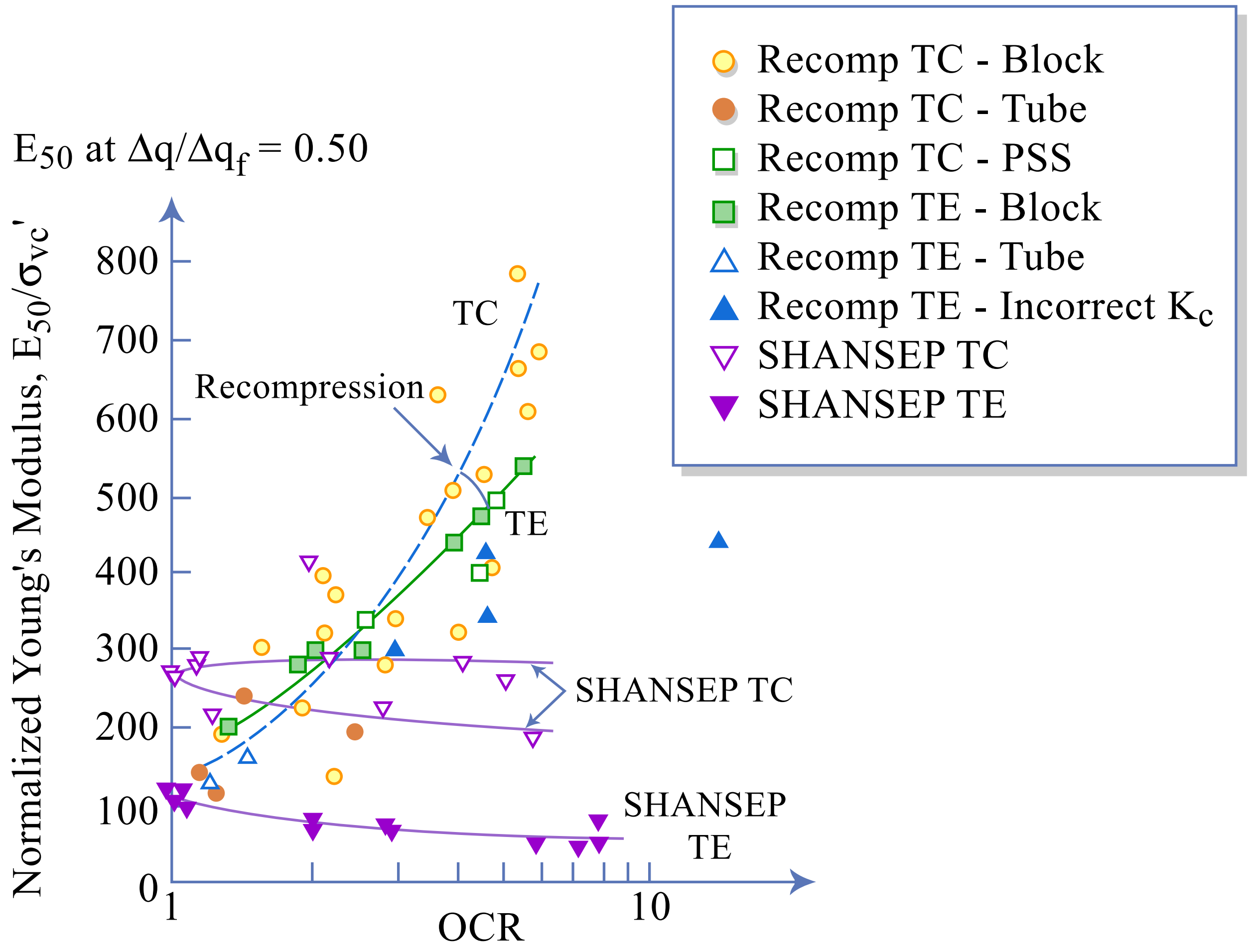
Settlement Ratio vs. Applied Stress Ratio for Strip Load on Isotropic Homogeneous Foundation

Figure by MIT OCW.

Adapted from: **D'Appolonia, Poulos and Ladd, 1971**

CCL 3/16/92 1.322 Consolidation V (E_u for Predicting P_c)
3/97

Comparison of E_{50}/σ'_{vc} vs OCR
from SHANSEP & RECOMPRESSION
CK_0UC/E Tests on Natural
Boston Blue Clay
(CA/T STP)



Normalized Young's Modulus vs. OCR for SHANSEP and Recompression Triaxial Compression and Extension Tests on Tube and Block Samples

Figure by MIT OCW.

Adapted from: Estabrook, 1991

Ⓒ

C.C. Ladd
1.321 M.I.T
4/72

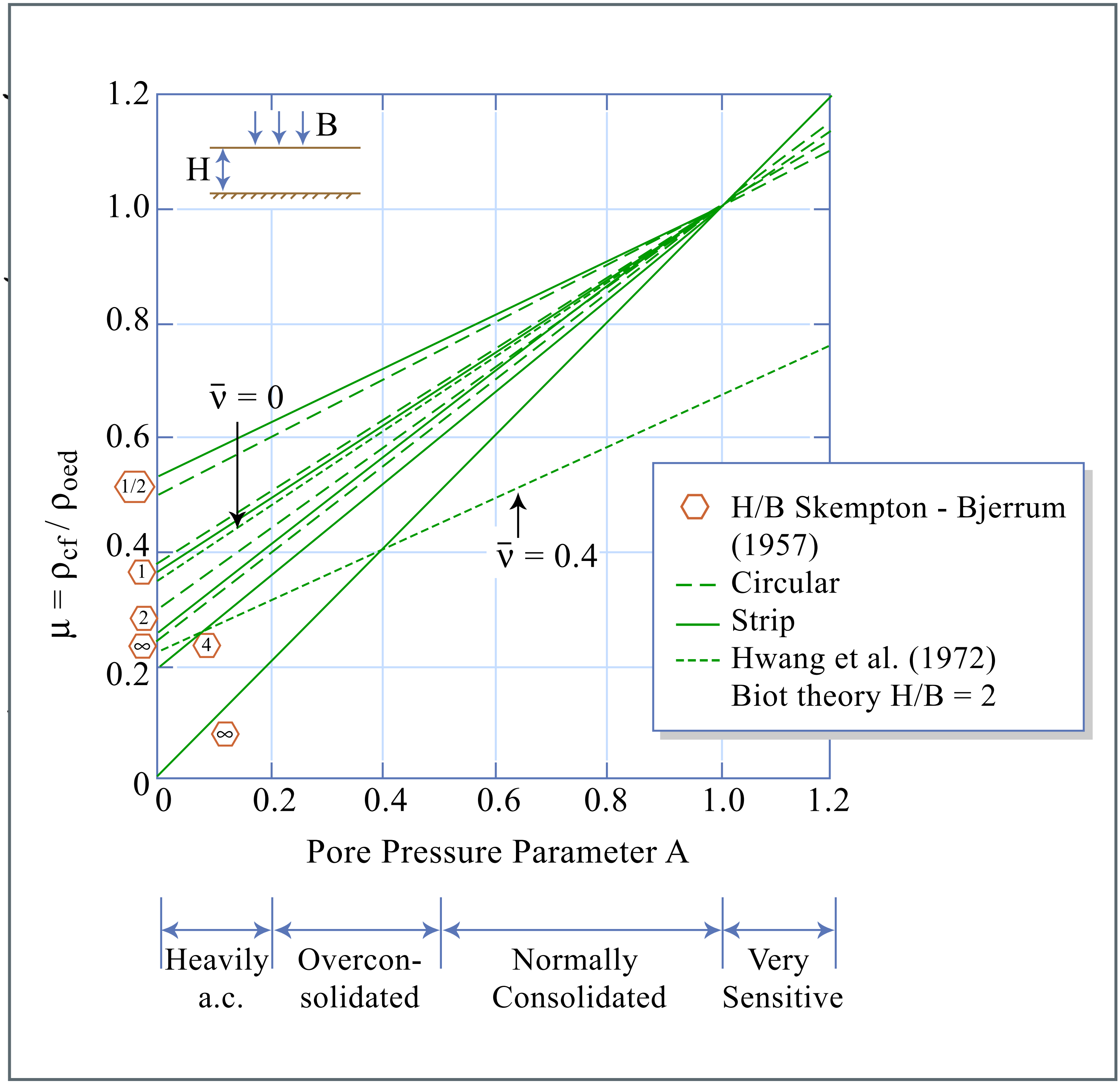


Figure by MIT OCW.

Adapted from: Meyerhoff (1958) Geot. Vol 8 No. 2 p 101

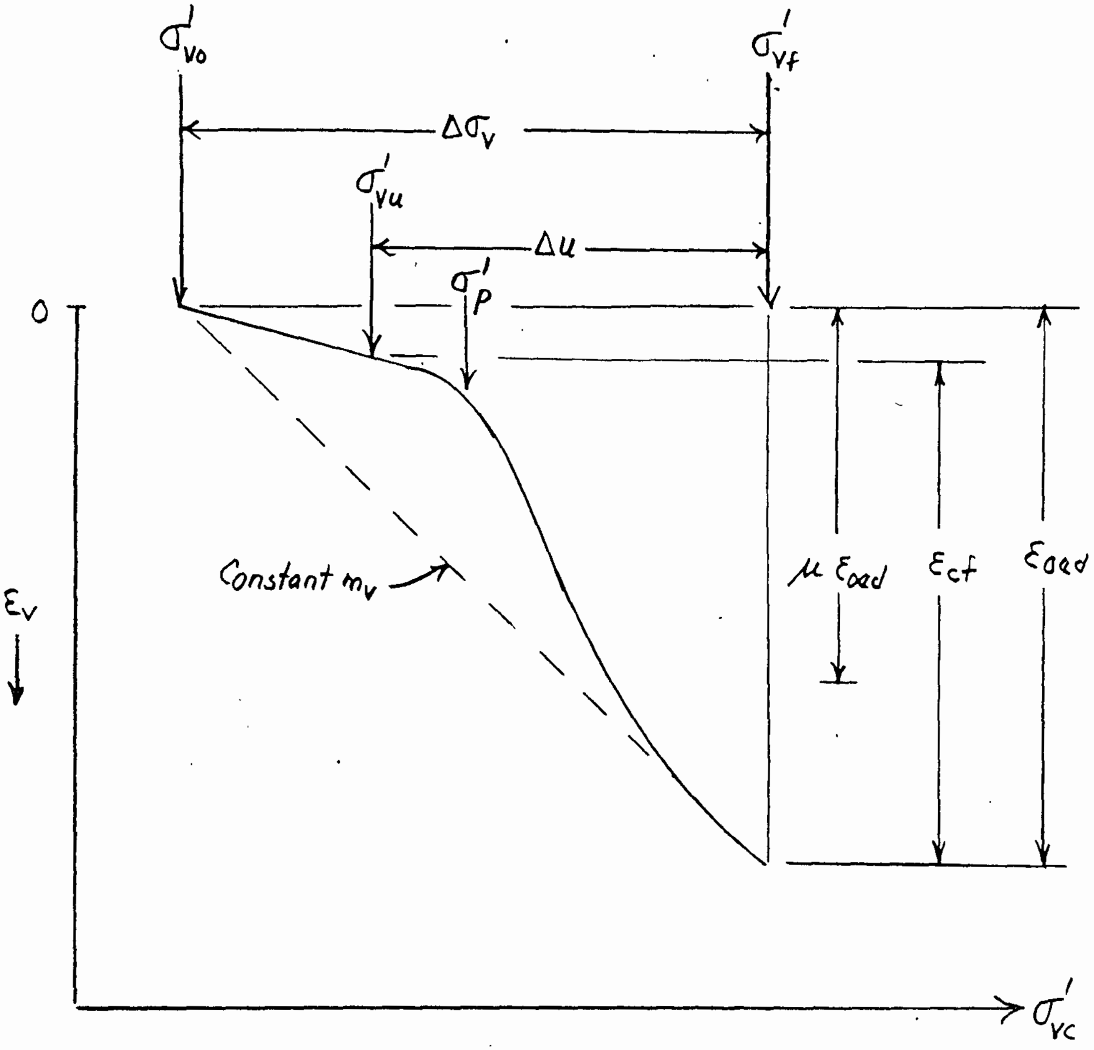
$\mu = 1 - \frac{3(1-A)}{4+B/H}$ for circular or square areas

INFLUENCE OF A PARAMETER AND GEOMETRY ON THREE DIMENSIONAL VS ONE DIMENSIONAL FINAL CONSOLIDATION SETTLEMENT

CCL 3/97 3/99
1.322 Consol. Part V

D1

Fig. V5-2 Illustration of Why Skempton-Bjerrum (1957) Procedure Can Underestimate the Final Consolidation Settlement When Loading O.C. Clay Well Beyond In Situ σ'_p

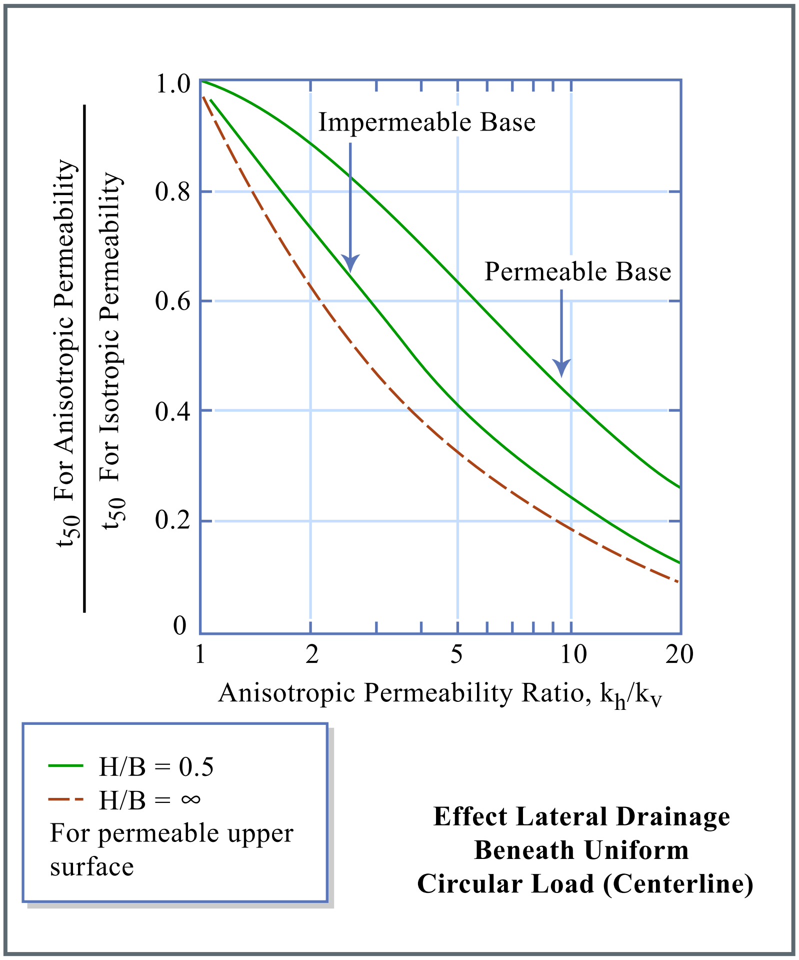


NOTE: Skempton-Bjerrum $\varepsilon_{cf} = \mu\,\varepsilon_{oed}$ illustrated for $\mu = \Delta u/\Delta\sigma_v = 2/3$

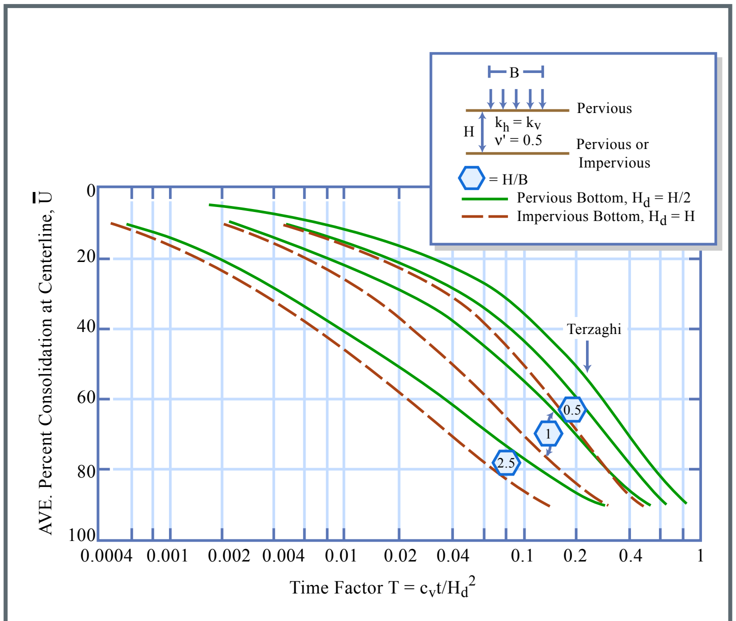
CCL 3/77

CCL 3/14/99

1.322 Consolidation Part V



Effect Lateral Drainage Beneath Uniform Circular Load (Centerline)



Effect Lateral Drainage Beneath Uniform Circular Load (Centerline)

Figures by MIT OCW.

Adapted from: Davis and Poulos (1972)

Effect Lateral Drainage Beneath Uniform Circular Load (Centerline)

(Ladd et al, 1977)

Ⓔ

- 1.364 MIT

1.322 .

Davis & Poulos (1968) Geotechnique 18(1) Use of elastic theory to predict settlements for isotropic, homogeneous soil conditions

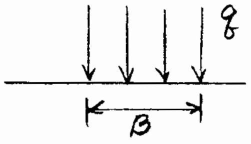
NOTE: Theory uses constant shear modulus → $E_u = 3G = \frac{3\bar{E}}{2(1+\bar{\mu})}$

Equations (Note: $\bar{E} = E'$; $\bar{\mu} = \mu' = \nu'$)

$$\left.\begin{array}{l} \rho_t = \frac{qB}{\bar{E}} I_\rho \text{ computed with } \mu = \bar{\mu} \\ \rho_i = \frac{qB}{E_u} I_\rho \quad \text{''} \quad \text{''} \quad \mu = 0.5 \end{array}\right\} \rightarrow \rho_{ct} = \rho_t - \rho_i$$

$$\rho_{oed} = \frac{qB}{E} I_\rho \quad \text{''} \quad \text{''} \quad \mu = 0. \ \& \ E = \frac{1}{m_v} = \frac{(1-\bar{\mu})\bar{E}}{(1+\bar{\mu})(1-2\bar{\mu})}$$

Example: ℄ Circular Load on Elastic Half Space



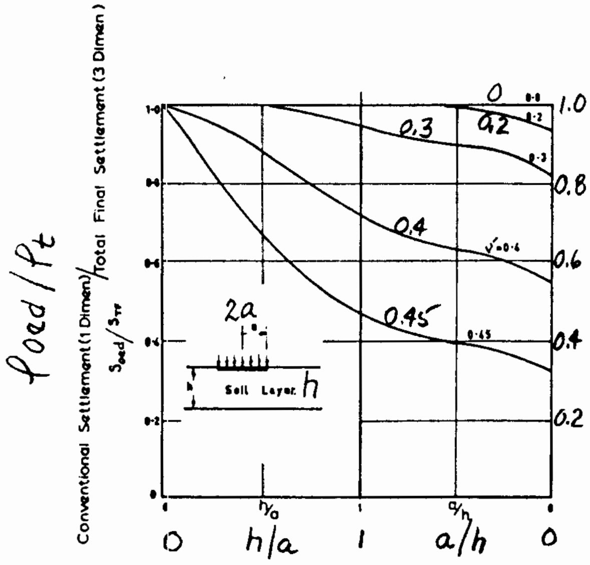
$$\rho = \frac{qB}{E}(1-\mu^2)$$

For $\bar{\mu} = 0.25 \rightarrow E_u = \frac{3\bar{E}}{2(1.25)} = 1.20\bar{E}$

$$\rightarrow \frac{1}{m_v} = \frac{(0.75)\bar{E}}{(1.25)(0.5)} = 1.20\bar{E}$$

$$\therefore \rho_t = \frac{qB}{\bar{E}}(1-0.25^2) = 0.9375\,qB/\bar{E} \ ; \quad \rho_i = \frac{qB}{1.2\bar{E}}(1-0.5^2) = 0.625\,qB/\bar{E}$$

$$\rho_{ct} = 0.3125\,qB/\bar{E} \ ; \quad \rho_{oed} = \frac{qB}{1.2\bar{E}}(1-0) = 0.8333\,qB/\bar{E} \rightarrow \begin{array}{l} \rho_i/\rho_t = 0.67 \\ \rho_{ct}/\rho_t = 0.33 \\ \rho_{oed}/\rho_t = 0.89 \end{array}$$



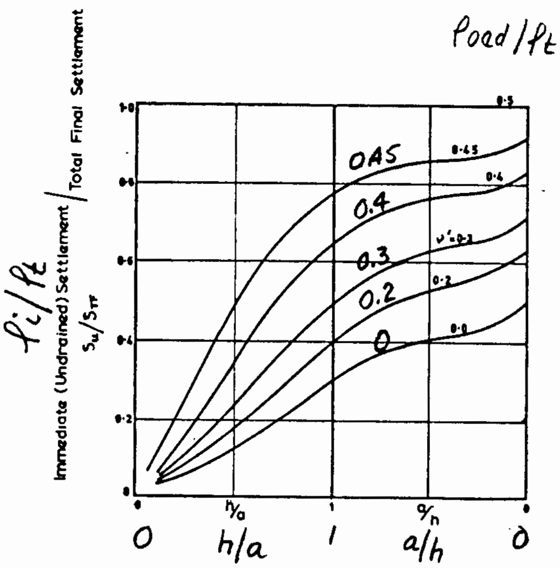


Fig. 1 (left). Errors in the conventional one-dimensional approach for total final settlement

Fig. 2 (right). Relative importance of immediate settlement

CONCLUSION: Overpredicts ρ_i/ρ_t Why?